USE OF SHUNT CAPACITORS FOR IMPROVEMENT IN POWER FACTOR AND VOLTAGE REGULATION

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SUMMARY

This bulletin contains a discussion of the use of shunt capacitors on primary lines. Methods of calculating capacitor ratings and suggestions for their installation and protection on primary lines are included.

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Inductive loads on distribution lines result in low power factor and are one of the causes of excessive voltage drops on the lines. The reactive power taken by the inductive load represents a real loss in that it requires additional system capacity and limits permissible load by voltage drop.

Shunt capacitors may be used to compensate for the low power factor of inductive loads, thereby permitting the release of system capacity, reducing line loss and providing a voltage rise to compensate for the drop due to the reactive power taken by the load. The shunt capacitor may also be used in conjunction with various regulating devices to provide better regulation.

I. THEORY OF OPERATION

The total kilovolt-amperes (product of kilovolts and amperes) carried by a distribution or transmission line, is composed of two components:

a. The "real" or "active" power
b. The "reactive" kilovolt-amperes

These components are related to the total kilovolt-amperes by the formula:

$$(KVA)^2 = (KW)^2 + (KVAR)^2$$

Where: KVA = Total kilovolt amperes
KW = Active power
KVAR = Reactive kilovolt-amperes

The ratio of the active power to the total KVA is termed the power factor. For single phase circuits or for three phase circuits with balanced loads, the power factor can be expressed as the cosine of the angle between the representative voltage and current vectors:

$$\cos\theta = \frac{KW}{KVA}$$

Where $\cos\theta$ = power factor
θ = angle between current and voltage vectors

When the current lags the voltage (angle θ is positive) the power factor is termed "lagging". When the current leads the voltage (angle θ is negative) the power factor is termed "leading".

The voltage drop along the line and the energy losses in the line depend upon the current carried, and therefore, upon the total KVA rather than on the active power in KW. The power factor of the load is therefore an important factor in determining the losses and voltage drops. In addition, the generating equipment and transformers must be of sufficient capacity to carry the total KVA. The smaller

the reactive KVA which must be supplied, the more closely does the total KVA equal the active or useful power, and the more efficient is the system operation. That is, the efficiency of system operation becomes greater as the power factor approaches unity.

Inductive loads, such as motors, consist of "positive" reactances (angle θ is positive) and therefore require certain amounts of lagging reactive KVA. The supply of this lagging KVAR requires the transmission of higher current than required for the active power component alone, thus increasing energy losses, causing greater voltage drop, and reducing system capacity.

A shunt capacitor is a negative reactance connected across the line, in opposition to the positive reactance of the inductive load. It draws a leading current which flows through the line reactance causing a voltage rise between the capacitor and power source which is proportional to the total line reactance. The lagging reactive KVA requirements of the load beyond the capacitor are also decreased by the amount of the leading reactive KVA taken by the capacitor. This results in a net power factor for the system which is closer to unity and consequently brings about a reduction in losses and a release of system capacity.

II. SYSTEM ANALYSIS PRIOR TO INSTALLATION OF SHUNT CAPACITORS

A. Information Required

The following information should first be obtained:

1. A map of the system showing:

   a. Size and location of important individual loads
   b. Wire sizes, lengths and phasing

2. Distributed load at light and full load

3. Size and power factor of large inductive loads at light and full load

4. Kw and reactive kva (or power factor) of the system at light and full load periods

5. A voltage regulation study of the system

6. Type and location of existing voltage regulators

B. Voltage Gradient Diagram

Plot a voltage gradient diagram of the system under consideration similar to Figure 1, for full load and light load periods.

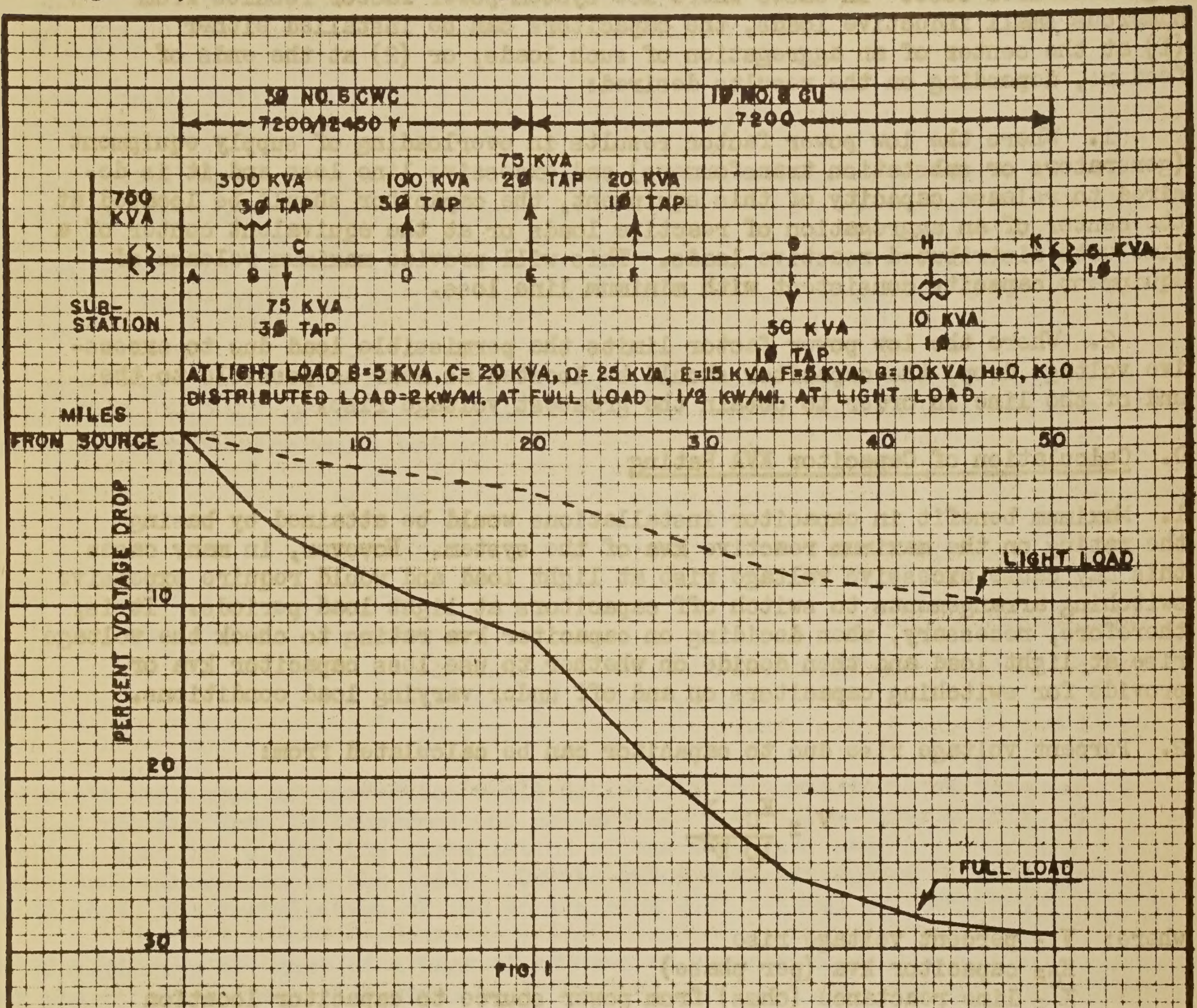

FIG. 1

C. Determine Location of Capacitors.

Where large inductive loads occur on the system, it is generally possible to make arrangements for installation of the capacitor at the load by the consumer. In such cases penalties for low power factor usually contribute to encourage such installations by the consumer and the capacitors are switched on and off the line with the loads. Such loads then act practically as resistive loads and do not cause a decrease in the power factor of the system. When such arrangements are impossible or not feasible, or where lagging power factor is due to small distributed reactive loads, capacitors must be installed on the primary lines.

In general, capacitors should be located as close as possible to large inductive loads in order to eliminate reactive kva at its source. However, very small capacitor units should generally be avoided due to the relatively high installed cost. In cases where low system power factor results from numerous small inductive loads, the capacitors can be installed either (1) at the center of an aggregation of such loads, or (2) at the ends of feeders, depending on the results desired:

1. Where the low power factor results in overloading of supply equipment (generators or substation transformers) and excessive line loss and it is desired to release capacity of this equipment, the capacitor should be located at the center of an aggregation of reactive loads or at the equivalent center of a line with distributed reactive loads. This will provide maximum release of equipment capacity consistent with minimum line loss.

2. Where the low power factor limits the permissible load due to excessive voltage drop, the capacitor should be located as near as possible to the end of the line in order to obtain the greatest voltage rise.

D. Calculation of Capacitor KVA Rating

1. Maximum benefit in capacitor installations would be attained by basing the rating on the maximum reactive kva of the system. However, in many cases this may cause excessive voltage rise at light load and would require expensive switching arrangements to switch off capacitors at light load periods. It is, therefore, necessary, when deciding on capacitor kva rating to check the voltage rise at light load and then decide on whether to use less capacitor kva or provide for switching capacitors on and off under varying load conditions.

2. Percent voltage rise due to capacitor can be calculated from:

$$V = \frac{K_C \ X}{10 \ E^2}$$

where: V = percent voltage rise
K_C = capacitor kva (per phase)
X = line reactance (ohms) from power source to capacitor location
E = line to neutral kilovolts

3. Plot a diagram showing the voltage rise along the system due to the capacitor, and the total voltage gradient due to sum of the gradient of Figure 1 and the rise due to the capacitor.

E. Example.

1. Assume a system as illustrated in Figure 1.
Power factor at light load = $\cos \theta_N = 0.9$
Power factor at full load = $\cos \theta = 0.75$
Light load = K_{LN} = 105 kva (3 ϕ)
Full load = K_L = 735 kva (3 ϕ)
Line reactance between A and E = 0.885 ohms per mile
Line reactance between E and K = 1.577 ohms per mile

2. Calculate reactive kva at full load and at light load.

Θ_N = arc cos 0.9 = 26.2 degrees
Θ = arc cos 0.75 = 41.4 degrees
sin Θ_N = 0.44
sin Θ = 0.66

reactive kva at full load = 735 x 0.66 = 485 kva (3 ϕ)
reactive kva at light load = 105 x 0.44 = 46 kva (3 ϕ)

A fixed capacitor installation of 46 kva may be made or capacitors totalling 485 kva may be installed with automatic switching to reduce the amount of capacitor kva at light load if excessive voltage rise occurs at light load. A third method may be the installation of smaller capacitor units at the individual large loads on the line which will be switched on and off with the load.

3. Where the correction employed is the installation of one capacitor bank of 46 kva at the end of the three phase line, the percent voltage rise at the capacitor installation would be:

$$V = \frac{K_C X}{10 E^2}$$

where K_C = 1/3 x 46 = 15.3 kva
X = 20 x 0.885 = 17.7 ohms

$$V = \frac{15.3 \times 17.7}{10 \times 7.2^2} = 0.52 \text{ percent}$$

Obviously this type of correction would not result in any benefit as far as reduced voltage drop is concerned and one of the other two methods must be applied; that is, either the installation of one capacitor bank of 485 kva or individual capacitors at the loads. On the other hand, if equipment capacity is limited, the installation of the 46 kva bank will release some capacity.

4. Considering the case of a bank of 485 kva of capacitors or 1/3 x 485 = 161.8 kva per phase, the voltage rise would be:

$$V = \frac{161.8 \times 17.7}{10 \times 7.2^2} = 5.5 \text{ percent}$$

The voltage gradient would then be represented by Figure 2.

It may be seen from Figure 2 that in this case the maximum voltage rise (at point E) is only 2% above normal rated voltage. This would not require any switching of capacitors and the full bank of 485 kva could be installed for permanent connection.

5. It should be noted that this capacitor installation has not improved voltage regulation and that some type of regulator must be installed if it is desired to limit the voltage variation between light load and full load.

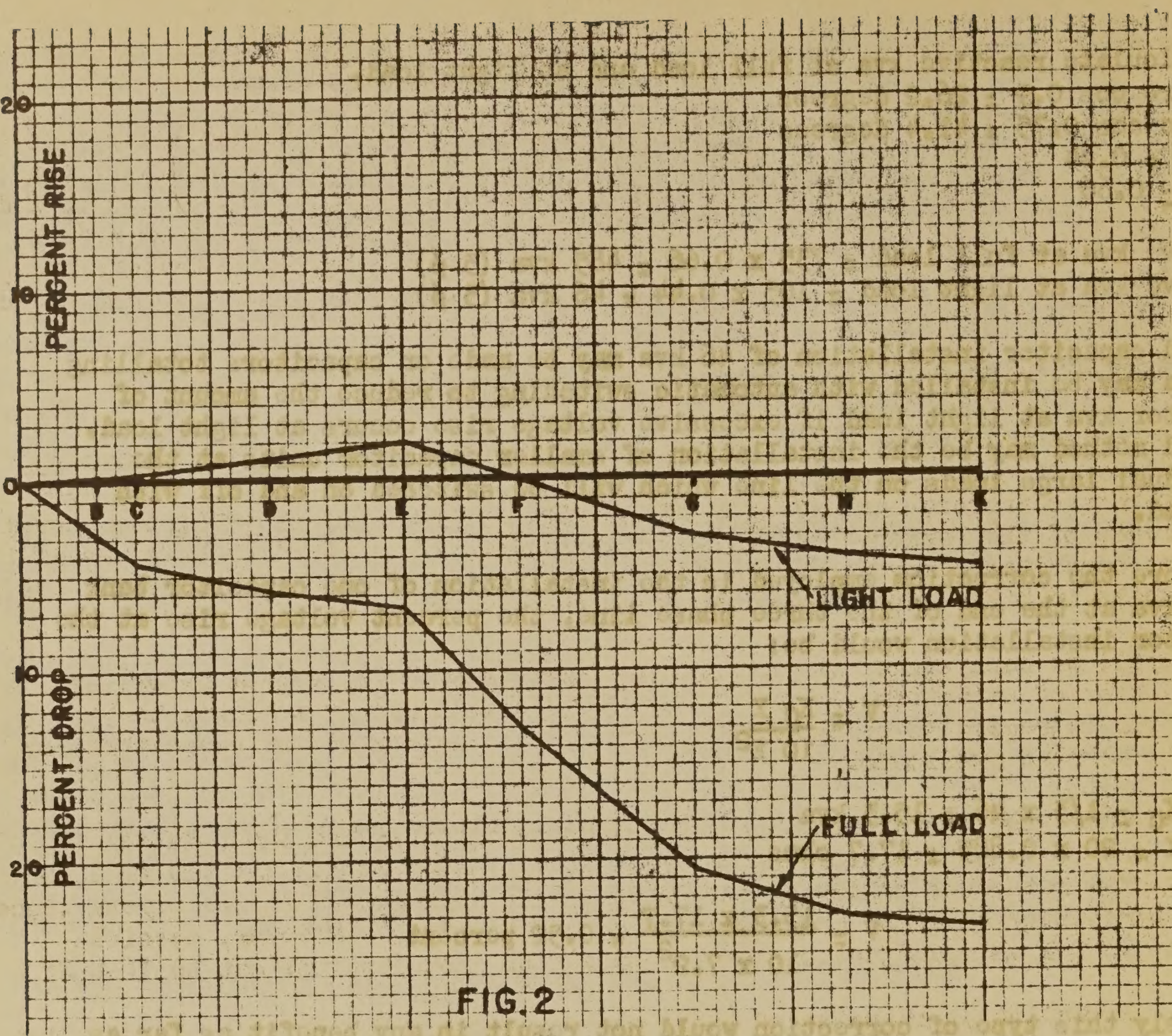

FIG. 2

III. VOLTAGE RATING OF CAPACITORS

Shunt capacitors must be rated for full line to ground voltage when Y connected or for line to line voltage when delta connected. While capacitors are designed to allow operation at approximately 115% of rated voltage, the allowable margin will be reduced by the presence of harmonic currents in the circuit. For this reason it is best to restrict operation to a maximum of 105% of rated capacitor voltage where presence of harmonic currents is suspected.

IV. LIGHTNING PROTECTION AND FUSING

Although shunt capacitors installed in Y connected banks on multi-grounded neutral lines will reduce in some degree the maximum impulse voltage due to lightning, it is recommended that all shunt capacitors be protected by line-type arresters. The ability of the shunt capacitor bank to slope off the wave front and reduce the peak of a travelling wave will afford increased lightning protection to transformers and other line equipment installed in the vicinity of the capacitor bank.

Capacitors should be connected to the line with fused disconnects. Fuse ratings should be based on a liberal overload current to prevent fuse burn-outs on transient currents.

V. CHOICE OF DELTA OR Y CONNECTION OF THREE PHASE CAPACITOR BANKS

In general, Y connected banks should be installed on multi-grounded Y lines to take advantage of the additional lightning protection afforded by the capacitor action. However, when this installation causes telephone interference, conversion to a delta bank may alleviate the trouble. A Y connected bank may be installed on a delta line only with suitable ground relaying equipment for protection, since failure of one capacitor would impress full line to line voltage across the other two and may cause their failure.

VI. EFFECT OF SHUNT CAPACITORS ON TELEPHONE INTERFERENCE

Shunt capacitors in themselves are not sources of harmonic currents. However, the addition of shunt capacitance in the line will affect the circuit impedances. Where harmonic currents are present in the circuit, this may cause either increase or decrease of the harmonic currents and voltages. Thus, in some cases the addition of shunt capacitance may decrease the amount of interference to paralleling telephone lines while in other cases it may increase the interference.

In general, an analysis of the system wave shape should be secured before the installation of capacitors is made. This will enable proper measures to be taken both in regard to telephone interference and safety of the capacitor from harmonic current overloads.

In cases where the installation causes telephone interference the solution is in general one of inductive coordination between the power system and the telephone system. The method of relieving the interference will depend on the circumstances of the particular case and no general rules can be given. However, possible remedies as far as modifications of the capacitor installations can be listed:

1. Installation of balanced three phase capacitor banks on the three phase feeders instead of single phase units at the end of single phase taps.

2. Installation of delta banks instead of Y connected banks.

3. Use of a low voltage gap between the Y capacitor bank neutral and the line neutral on a multi-grounded system, instead of a direct connection. This gap should be set to break down when a fault occurs in one of the capacitors in order to prevent line to line voltage from being impressed on the remaining capacitors.

4. A change in size or location of the capacitor unit in order to change the circuit impedance so that harmonic currents are not increased.

5. Insertion of a reactor in series with the capacitor. The series combination should be arranged to act as a resonant shunt across the line at a frequency of about 300 cycles. This can be accomplished by making the 60 cycle impedance of the reactor equal to about 5% of the phase to neutral impedance of the capacitor. While this arrangement may increase the 180 cycle component somewhat, it will in general decrease harmonics above 300 cycles. Care should be exercised in the use of this method since, if 300 cycles is present in the system wave, the 300 cycle current through the capacitor may be excessive.

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